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COUPLED OCEAN-ATMOSPHERE INTERACTION AND THE DEVELOPMENT OF THE MARINE ATMOSPHERIC BOUNDARY LAYER

FINAL REPORT for N000149510827

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Summary
The goal of this research was to provide an understanding of the processes that control the structure of the marine atmosphere and its interaction with the ocean. In particular, we focussed on understanding the processes that control the exchange of heat and moisture between the ocean and the atmosphere and understanding the physical processes that control the formation, development and decay of stratocumulus clouds in the marine boundary layer.

These results have led to new insight into the interactions between cumulus and stratocumulus clouds in a marine layer capped by a temprature inversion. The results are applicable to the development of coupled ocean-atmosphere models where accurate information on the temperature of the sea surface is required. Generally, coupled models fail to resolve accurately the sea surface temperature because they do not include the cloud processes addressed in the present study.

Major findings

* Radiative heating of the cloud-capped marine layer is sufficient to cause the decoupling of the cloud and subcloud layers;

* This decoupling leads to the formation of a layer of cumulus clouds below the main stratocumulus cloud deck;

* The sea surface temperature plays an important role in the formation of the penetrative cumulus clouds;

* The cloud liquid water content in the stratocumulus generally increases locally in a region of penetrative cumulus; however, changes in the droplet spectra due to mixing depend on the individual drop spectra of the two cloud types;

* The droplet spectra is influenced by the aerosol characteristics of the boundary, the updraft velocities of the cumulus and the cloud thickness of the stratocumulus and cumulus layers;

* The cumulus may enhance the stratocumulus deck or cause it to break up depending on whether the cumulus can force the entrainment of dry, warm air from above the inversion;

* The effects of penetrating cumulus clouds on the droplet effective radius in stratocumulus, ane hence on the cloud radiative properties, may differ significantly between boundary layers;

* Data from ASTEX showed that in regions where cumulus clouds penetrate the base of stratocumulus clouds, the stratocumulus layer is thickened. The increase in available moisture within the penetrating cumulus clouds results in an increased liquid water content and hence changes in the droplet size spectra;

moisture within the penetrating cumulus clouds results in an increased liquid water content and hence changes in the droplet size spectra;

* The greater liquid water path results in a larger optical depth, which can be observed by satellite;

* These cumulus-stratocumulus interactions will alter the surface energy budget and must be considered in any model of the marine layer.

Approach and Background

We used a combination of observational studies and numerical models to investigate the marine atmospheric boundary layer structure and its interaction with the ocean. We completed two related field programs and developed a new modeling technique to simulate the detailed physiscal structure of the marine atmosphere. The Internal Boundary Layer Experiment (IBLEX) conducted around the U.K. coast (Rogers et al. 1995a and b) and the Atlantic Stratocumulus Transformation Experiment (ASTEX) in the Azores (Rogers et al. 1995c, Martin et al. 1995, 1997) provided detailed in situ measurements of marine boundary layer clouds.

While the primary focus of this work was the analysis of ASTEX data, other related, ONR supported, field studies contributed to our findings. These include, the Coupled Ocean Atmosphere Response Experiment (COARE) in the western Pacific (Serra 1997, Serra et al 1997), SHAREM 115 in the Persian Gulf (Brooks et al. 1997) and the Coastal Waves Experiment 1996 (CW96) off the coast of California (Rogers et al. 1997), and the Monterey Area Ship Tracks (MAST) Experiment (Brooks and Rogers 1997).

TOGA COARE was concerned primarily with the processes that control the structure of the surface layer in the tropics. SHAREM 115 extended the study of the marine boundary layer into a coastal region, characterized by a high aerosol content and high humdity, and tested our ability to collect environmental data in a warfare scenario. CW96 was developed to investigate the structure of the stable coastal boundary layer off the west coast of the US, building on our undersanding of coherent fields observed during MAST, the stable boundary layer studies of IBLEX and the cloud observations of ASTEX.

Tasks Completed

* Completed a comprehensive study of cumulus and statocumulus interactions observed during ASTEX.

* Developed a smooth particle hydrodynamic model to apply to the ASTEX data. Dr. Peter Norris was awarded the Ph.D. from UCSD for this work.

* Completed a study of the processes that couple the ocean and atmosphere in the tropics. Dr. Yolande Serra was awarded the Ph.D. for this work.

* Published papers in the Journal of Atmospheric Sciences, Quarterly Journal of the Royal Meteorological Society and the Journal of Geophysics. Contributed to numerous conference proceedings.

* We have demonstrated the integration of a basic research program with an applied program supporting systems testing in SHAREM 115. Completed the processing of aircraft data collected during SHAREM 115. These data have been given to NRL Monterey to aid in the development of aerosol models and to test electromagnetic systems. A separate award supports the continuation of this work.

* Completed the processing of aircraft data collected during CW96. Preliminary results have been shared with NRL Monterey to help test the COAMPS model. We have demonstrated that COAMPS model performed well during the experiment providing forecasts of wind fields in agreement with the aircraft observations. A separate award supports the continuation of this work.

Scientific results
* The structure and evolution of the marine boundary layer depends largely on the variability of stratus and stratocumulus clouds. Stratus clouds are generally associated with a well-mixed boundary layer, whereas daytime observations of stratocumulus-topped boundary layers generally indicate that the cloud and subcloud layers are decoupled. In ASTEX, aircraft measurements showed a surface-based mixed layer, separated from the base of the stratocumulus, by a layer that is stable to dry turbulent mixing. The transition layer forms due to shortwave heating of the stratocumulus clouds. Cumulus clouds often develop in the transition layer and they play a fundamental role in the redistribution of heat in the decoupled stratocumulus-capped boundary layer. They are, however, very sensitive to small changes in the heat and moisture in the boundary layer and are generally transient features that depend directly on the surface sensible and latent heat fluxes. The cumulus clouds contribute a bimodal drop-size distribution to the stratocumulus layer skewed to the smaller sizes but may contain larger drops. Clouds increase at night in response to the combined effect of convection, which can transport drops to the top of the boundary layer, and outgoing longwave radiation, which cools the boundary layer. The relationship between the cumulus clouds and the latent heat flux is complex. Small cumulus may enhance the flux, but as more water vapor is redistributed vertically by an increase in convective activity the latent heat flux decreases. The illustrates the need for boundary layer models to properly handle the occurrence of intermittent cumulus to predict the diurnal evolution of the stratocumulus-capped MABL and for coupled models to predict changes in the sea surface temperature.

* Observations made during a series of lagrangian experiments in ASTEX were used to investigate how the properties of a stratocumulus layer in which cumulus clouds are interacting differ from those of a stratocumulus layer without penetrating cumulus. In regions where cumulus clouds penetrate the cloud layer, the stratocumulus deck is thickened as the cumulus spread into its base. Transport of air from the surface based mixed layer (subcloud layer) by convective updrafts was observed, and the increase in available moisture within the penetrating cumulus clouds results in an increased liquid water content and hence changes in the droplet size spectra. The greater liquid water path results in a large cloud optical depth, thus regions where cumulus are interacting with the stratocumulus layer can be observed in satellite measurements.

* The dependence of these changes as a function of air mass type was also investigated. Using data from ASTEX, FIRE (California stratus) and IBLEX, the effects of different thermodynamic properties and different levels of pollution were studied. Although cloud liquid water content in stratocumulus generally increases locally in a region of cumulus cloud penetration, the changes in the droplet spectrum, which result from mixing between the cumulus and stratocumulus droplets, depend on the individual droplet spectra in the two cloud types. This, in turn, is influenced by the aerosol characteristics in the boundary layer, the updraft velocities associated particularly with cumulus clouds, and the actual and relative cloud thickness of the cumulus and stratocumulus. The effects of penetrating cumulus clouds on the droplet effective radius in the stratocumulus, and hence on the cloud radiative properties, may therefore differ significantly between boundary layers in which the interaction occurs.

* Most existing numerical solutions in computational fluid dynamics use the widely studied Eulerian approach, that is, prognosis of field variables at fixed locations within the domain. By contrast, smoothed particle hydrodynamics (SPH) is a Lagrangian technique, that is, it makes prognosis at positions that follow fluid elements within the domain. The technique was designed to deal with the unbounded simulations required in astrophysics, but finds increasing application in a variety of problems, ranging from high speed metallic impact to wave generation. Lagrangian methods require that the equations of motion be evaluated at a set of disordered points representing small fluid elements. The advective terms, which are difficult to evaluate in an Eulerian framework due to inherent non-linearity, are simply evaluated in a Lagrangian framework, because the prognosis positions are, by definition, advected with the local fluid velocity. This makes the method very amenable to other parcel processes, such as cloud microphysics, for example. Non-local processes, however, such as those involving the calculation of field gradients, are not so trivial. These gradients are estimated by first interpolating from the disordered fluid element positions and then using the gradients of the interpolation. In SPH, the fluid is divided into a large but finite number of elements, which are localized as so-called "particles". Interpolation is then accomplished using a local weighting function, called the kernel, which distributes the properties of the fluid about the disordered positions of these particles. The kernel has some small finite range, which implies that the properties of a given particle are only affected by those other particles, called "neighbors", which fall within a certain range of the particle in question. We have applied the SPH method to the atmosphere, with a view to performing improved simulations of the cloud-topped marine boundary layer (CTMBL). The first part of our work has involved designing a code to model the SPH equations for a stratified geophysical fluid. This involves a basic time-stepping routine for the compressible Navier-Stokes equations, a special design to allow efficient collection of near-neighbor particles and a system for correctly initializing particle positions. In addition, we devised a new type of boundary condition to handle particle-wall interactions within a stratified fluid. The code has been written for operation on parallel machines, and an initial series of test runs (sound propagation, viscous diffusion, and buoyancy oscillations) indicate the method to be robust and accurate.

* We completed a study of aircraft measured surface fluxes in the vicinity of deep cumulus convection over very warm water and in suppressed conditions over cooler sea surface temperatures in the tropics. Despite the light winds observed during COARE (<3 m/s), a wide range of convective conditions was observed. Within the surface layer, the convective conditions were divided into three categories; forced convection, free convection and a transition region, which is a mixture of free and forced convection. Free convection, where buoyancy dominates over mechanical production of turbulence in the boundary layer, results in enhanced surface heat and buoyancy fluxes for the given wind conditions, compared with those observed for forced conditions.

While the temperature of the warm pool region in COARE was found to be largely independent of local conditions measured by the aircraft, we observed that the warmest temperatures (>30 C) coincide exclusively with the lightest winds. This highlights the importance of wind-driven mixing in determining the thermal structure of the upper ocean.

* The COARE bulk flux algorithm was tested further with data from other experiments and a slightly revised version of the code released. Estimates of the surface fluxes within a convective region of COARE indicate that the bulk flux algorithm captures the overall spatial patterns of the sensible and latent heat fluxes. However, large discrepancies exist for the momentum flux. This occurs because the source of the velocity variance is associated with the convective activity, which is consistent with our observations from MAST. The latter results show that organized rolls can transport large amounts of momentum when compared with conditions observed outside of the roll regime.

* Preliminary results from CW96 lidar measurements reveal well-defined boundary layer coherent structures. Coincident, in situ turbulence measurements indicate that the stable boundary layer may be ventilated by discrete events that overturn the entire layer. These measurements are the first of which we are aware that combine lidar and turbulence measurements on a single airborne platform.

* Preliminary results from CW96 also address the problem of fog formation and boundary layer cloud development. Measurements of the surface fluxes, boundary layer depth and the air-sea temperature difference reveal that fog forms quite often at the boundary between stable and unstable air. A large latent heat flux enables a very shallow boundary layer to saturate quickly forming fog. Further offshore, with increased buoyancy the boundary layer depends and the fog lifts to form a stratus or stratocumulus cloud layer.

Significance

* We have demonstrated the importance of resolving cumulus-stratocumulus cloud interactions to properly resolve the structure of the marine atmosphere. This has important implications for the surface energy balance and must be considered in any coupled ocean-atmosphere model to properly predict the evolution of the sea surface temperature, and hence apply to appropriate boundary condition for the ocean model.

* We have demonstrated that the SPH model is useful tool that can be applied to a variety of atmospheric processes. While we have focused primarily on the development of clouds in the marine boundary layer, we anticipate that we will be able to apply the same technique to interactions of the atmosphere and ocean. This will include the effects of surface gravity waves on the exchange of momentum across the air-sea interface.

* The COARE results highlight the importance of considering free convection in the parameterization of surface fluxes and the likelihood of large errors, if the effects of buoyancy on the vertical velocity variance in light winds is not considered.

* We have provided the scientific community with a more accurate algorithm to calculate surface fluxes from ship and buoy data. This algorithm is available for testing in global models and could be provided to NRL to test in the COAMPS model. Uncertainties exist in connecting the surface layer, Monin-Obukhov similarity theory to large scale, coherent, convective and shear driven processes that may dominate the boundary layer structure. These need to be tested in a high resolution mesoscale model.

* The CW96 lidar and turbulence measurements afford us the opportunity to understand the structure of the stable coastal boundary layer in great detail. These observations will reveal the spatial scales and processes that control the exchange of heat, moisture and momentum between the surface layer and the free atmosphere. The results will lead to a better parameterization of the coastal region in regional models and a better understanding of the spatial variability of aerosols in the coastal regime. The latter will be applicable to electromagnetic propagation problems in the littoral zone.

* The CW96 cloud and boundary layer observations indicate that we should be able to improve the prediction of formation and distribution of fog on scales much smaller than the current operational model grid scale, which may aid in the development of an appropriate parameterization.

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